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14. ABSTRACT
The project had two main objectives. The first objective was to measure the 15 m depth circulation in South China Sea and in the Luzon Strait region during fall and winter (October through January) with Surface Velocity Program (SVP) drifters and to measure the upper ocean mass transport through the Luzon Strait. The time period was chosen because a significant intrusion of the Kuroshio in the South China Sea through the Luzon Strait is known to occur during these months.
The second objective was to use drifting instruments to measure vertical profiles of velocity and temperature within large amplitude, non-linear internal waves and to compute their phase velocity and the magnitude of the non-linear terms.
The third objective is to use the existing and new datasets of surface circulation to compare with the results of the ROMS numerical model to evaluate the model ability to reproduce a realistic flow field in the Kuroshio region and in the East China Sea.

15. SUBJECT TERMS
Wave dynamics in the South China Sea, surface circulation and Kuroshio interactions with the East and South China Seas.

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FINAL TECHNICAL REPORT FOR:

"Non Linear Internal Wave Dynamics in the South China Sea - Analysis of NCOM surface circulation and sea level"

ONR Award #:ONR- N00014-03-1-0474

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LONG TERM GOALS

The long-term objective is to understand the dynamics of the several physical processes that occur in the China Seas with the coordinated use of several tools, some of which already developed by ONR: a numerical model, a Surface Velocity Program (SVP) drifters array and surface drifters are configured to gather enhanced data i.e. drifting thermistor chains fitted with profiling ADCP's (ADOS-A). This research contributes to a more realistic prediction of this complex physical environment in area of strategic importance for PACFLEET operations.

OBJECTIVES

The first objective was to measure the 15 m depth circulation in South China Sea and in the Luzon Strait region during fall and winter (October through January) with Surface Velocity Program (SVP) drifters and to measure the upper ocean mass transport through the Luzon Strait. The time period was chosen because a significant intrusion of the Kuroshio in the South China Sea through the Luzon Strait is known to occur during these months.

The second objective was to use drifting instruments to measure vertical profiles of velocity and temperature within large amplitude, non-linear internal waves and to compute their phase velocity and the magnitude of the non-linear terms.

The third objective is to use the existing and new datasets of surface circulation to compare with the results of the ROMS numerical model to evaluate the model ability to reproduce a realistic flow field in the Kuroshio region and in the East China Sea.

APPROACH

To accomplish the first objective, SVP drifters were assembled in Korea and deployed between 2003 and 2006, for three consecutive years, in the Luzon Strait region during the Kuroshio inflow regime of the October-January period from voluntary observing ships. In the 3rd year, deeper currents were also measured with drifters drogued at 150 m depth.

To accomplish the second objective Dr. Centurioni and Dr. Niiler have used a novel drifting instrument, the Autonomous Drifting Ocean Station with ADCP (or ADOS-A, Figure 1). Several ADOS-As were deployed in two separate experiments (2005 and 2007) in conjunction with arrays of SVP drifters.

To accomplish the third objective Dr. Lee performed various runs of the numerical model (ROMS), made under an appropriate range of settings and forcings, which were analyzed in terms of the East China Sea budget of mass, vorticity and thermal, potential and mechanical energies.

WORK ACCOMPLSHED

<u>Circulation studies in the South China Seas and interaction with the Kuroshio</u>

259 SVP drifters were deployed from Voluntary Observing Ships between October 2003 and January 2006 within the Luzon Strait. An additional 75 drifters drogued at 150 m depth were

deployed in the Luzon Strait from the ships operated by Hanjin Shipping Co thus completing the field work phase in 2005. The data from the SVP drifters drogued at 15 m depth were analyzed and the results published. The SVP drifter data (position, velocity and sea-surface temperature) are publicly available through AOML (NOAA).

Observations of large amplitude non linear internal waves in the South China Sea

Dr. Centurioni and Dr. Niiler have designed and built the ADOS-A, a new instrument to measure vertical temperature and velocity profiles in the upper ocean, to a depth of 200 m. Two separate deployments were performed in 2005 and 2007 with arrays of 4 and 8 ADOS-A respectively. Additional arrays of SVP drifters, some with GPS tracking capabilities, were used to support the internal wave experiments. The data were analyzed and the results are being published in a peer reviewed journal.

RESULTS

Surface currents in the northern South China Sea, Taiwan Strait and Kuroshio intrusions into the South China Sea

- Velocity observations near the surface made with Argos satellites tracked drifters between 1989 and 2002 provide evidence of seasonal currents entering the South China Sea from the Philippine Sea through the Luzon Strait. The drifters cross the Strait and reach the interior of the South China Sea only between October and January with ensemble mean speeds of 0.7 ± 0.4 m s^{-1} (Figure 1); daily mean westward speeds can exceed 1.65 m s^{-1}. The majority of the drifters that continued to reside in the South China Sea made the entry within a westward current system located at ~20 °N which crossed the prevailing northward Kuroshio path. In other seasons, the drifters looped across the Strait within the Kuroshio and exited along the south coast of Taiwan. During one intrusion event, satellite altimeters indicated that directly west of the Strait anticyclonic and cyclonic eddies resided, respectively, north and south of the entering drifter track. The surface currents measured by the crossing drifters were much larger than the Ekman currents that would be produced by a 8–10 ms^{-1} north–east monsoon, suggesting that a deeper westward current system, as seen in historical water mass analyses, was present (Centurioni et al. 2004)

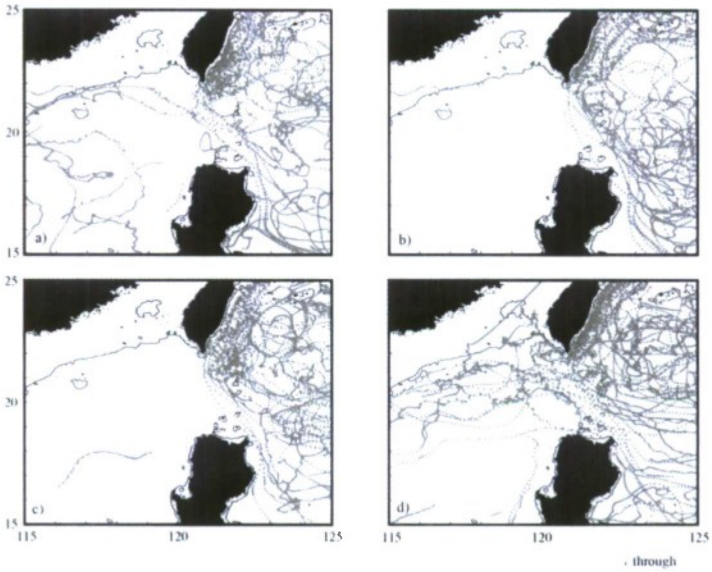

Figure 1: Seasonal displacement diagram of the drifters. a) Jan-Mar. b) Apr-June. c) Jul-Sept. d) Oct-Dec.

- On May 7 2005, 25 Surface Velocity Program drifters drogued at 15 m depth were deployed in the South China Sea (SCS), west of the Luzon Strait in a 5X5, 1.5 nm spacing, square array centered at 20° 27' N, 119° 33' E. All drifters mounted an Argos transmitter and a GPS receiver. The objective of this experiment was to measure the surface expression of the internal tide and non-linear internal waves that reach their maximum amplitude during spring tides. We show a remarkable dispersion of near-surface particles that can occur in the SCS at the onset of the Southwest monsoon. Eight selected trajectories illustrate very different processes that occur in the SCS and at its boundaries, such as strong internal tides, vigorous stirring by the mesoscale eddy field and interaction of mesoscale structures with the Kuroshio. The drifters, deployed within 19 km of each other, moved coherently to the south-west/west for about 6 days until they started to separate into 3 groups. The Summer monsoon in 2005 was established by June 15 and the associated Ekman currents can then push the drifters north-eastward. All drifters exited the SCS following very different routes (Figure 2). (Centurioni et al. 2007)

- Original velocity measurements at 15 m depth gathered from Surface Velocity

Program drifters deployed during this proposal are used to calculate the circulation in the South China Sea during the Winter Monsoon. The Ekman currents are computed with a new method and subtracted from drifter's velocity to calculate the residual circulation, which is approximately in geostrophic balance. The Ekman flow is nearly zonal and comparable to the zonal geostrophic flow in the northern basin. The geostrophic flow is cyclonic and extends into the southern Luzon Strait (Figure 3). Strong jets occur south of Hainan, off Vietnam and, to the south, off peninsular Malaysia. The Vietnam jet is concentrated inshore of the 200 m isobath, with mean speeds in excess of 1 ms^{-1}. The onshore Ekman transport and pumping velocity computed from the wind stress curl offers a qualitative explanation of the existence and behavior of such jets(Centurioni et al. 2009).

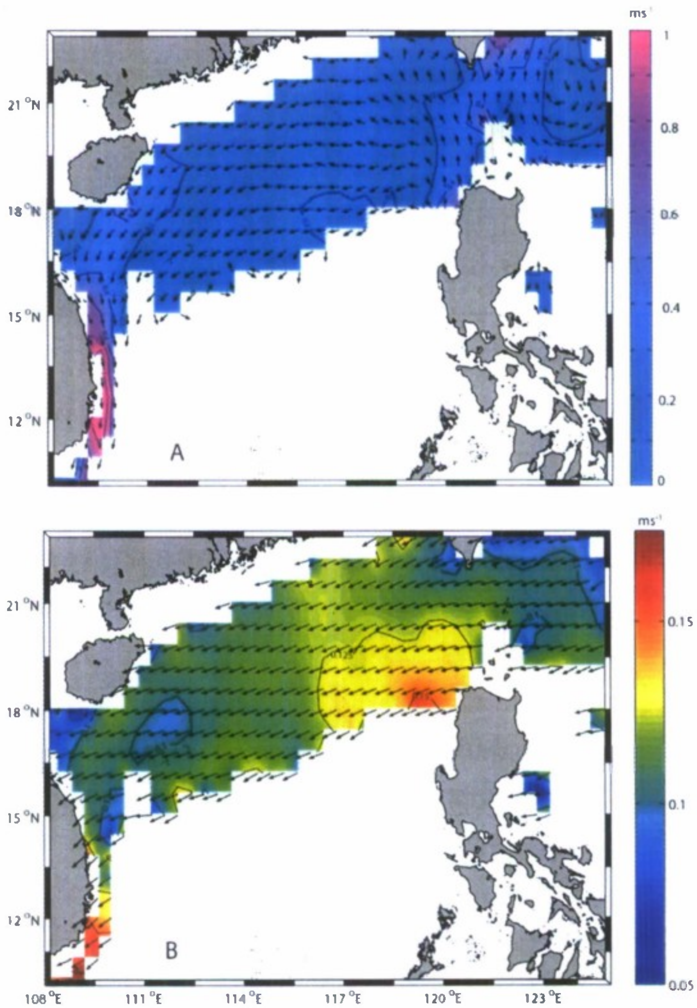

Figure 3: A) Mean 15 m geostrophic current (0.4° X 0.6°, ONDJ) from 11/12/1999 to 12/31/2007, computed over 49,220 six hourly observations. The pre-averaging operation in time within each bin yielded 10,293 independent velocity observations. The 200 m bathymetry contours are shown. B) Mean 15 m depth Ekman currents computed with QSCAT/NCEP blended ocean winds.

- Near the center of the northern South China Sea (NSCS), the Dongsha atoll is situated on the continental slope that runs from Taiwan to Hainan. A mesoscale cyclonic eddy, south or southwest of Dongsha, seems to appear annually and has been identified as the Dongsha Cyclonic Eddy (DCE). Historical drifter (1988–2005) and satellite altimeter (2000–2005) data were adopted to study the variations to, and characteristics of, the DCE. Some typical features were derived such as mean tangential speed of 20 cm/s, moving speed of 8 km/d (i.e., 9 cm/s), eddy size of 22 10^3 km^2, center sea surface lowering (height difference, DIF) of 6 cm, and angular velocity of 9 Deg/d. Mean tangential speeds of 12–16 cm/s in late spring and summer are slower than those of 16–31 cm/s in winter and early spring. Moving speeds are of the order of the Rossby wave at NSCS latitudes. Variations in the time series of eddy size and DIF are generally similar and show a positive linear relation between them. The DCE starts near Dongsha and moves southwestward along the continental slope at a depth of 1000–2000 m. The eddy peaks with maximum eddy size and DIF when reaching 114E, and then diminishes south of Hainan because of trapping of the underwater bay formed by the continental slope. The DCE typically exists 1–2 times per year and lasts 1–3 months. Roughly 90% of observed DCEs formed in winter or spring. A unique DCE was identified in the summer of 2000 and lasted for over 4 months. Its birth was associated with typhoon Kai-Tak. The positive linear relationship between eddy size and DIF in this case was unique before reaching 114_E and then returned to the typical relationship of other DCEs. The DIF of this unique DCE attained the highest of 24 cm right at the climax longitude. According to AVHHR and SeaWIFs images, such a DCE is associated with a core of which sea surface temperature is 2DegC lower and chlorophyll-a concentration is ~0.1 mg/m3 higher than those of surrounding seas. Migration of the DCE may be linked to tuna fish farms in the NSCS (Chow et al. 2008).
- The Taiwan Banks (Formosa Shoals), a large NE-SW oriented bathymetric feature near the southern end (23°N, 118–119°E) of the Taiwan Strait, is a region of extremely shallow water that exerts a profound effect on the propagation of tidal

waves. As such waves propagate over the Taiwan Banks, they become distorted and asymmetric due to the bottom friction and contribute to the generation of shallow water tides. The POM model was used in present study to simulate the tides in the Taiwan Strait region. Shallow water tidal dynamics in the area of Taiwan Banks are focused. The numerical model was validated against sea level observations from 34 tidal stations located on the coast of Mainland China and Taiwan. Trajectory records from two SVP drifters are used to be compared with the simulations using wavelet-based rotary spectral analysis. The numerical simulations show that the Taiwan Banks divides, separates and guides the southward propagating branch of M_2 tide along the western boundary of the Taiwan Strait as Kelvin Waves. The eastern branch, which dissipates its energy by the bottom friction around the Taiwan Banks and the Penghu Islands gradually diminished along the south-eastern boundary of the Taiwan Strait. The northward propagating M_2 dominates the tides in the waters east of the point 119.5E, 22.8N along the Penghu Channel instead. Moreover, the patterns of the standing waves of the 1/4 diurnal constituents are identified, it could be therefore hypothesized that the amplification of semi-diurnal tides in the Taiwan Strait are primarily due to the condition of two ends open channel co-oscillations. It is demonstrated by the numerical simulations as well as the SVP drifter record that the Taiwan Banks act as the generator of the shallow water tides. The shallow water constituents are amplified, propagate southward to the South China Sea and diminished rapidly. From the SVP drifter data short-time rotary spectral analysis, it is also interesting to note that the 1/5 diurnal constituent becomes significant compared to other shallow water constituents in the local vicinity of Taiwan Banks (Chiou et al. 2009)

- Surface Velocity Program drifters drogued at 15 m depth were deployed in the Taiwan Strait (TS) and Luzon Strait in 2005 and 2006. Three drifters in the TS and two drifter in the shelf-break of the East China Sea (ECS) were fortuitously overrun by the typhoon Hai-Tang (July 2005) and Shan-Shan (September 2006), respectively. From the drifter and QuikSCAT wind data it is clearly demonstrated that the current field over the TS and the shelf-break of ECS can be changed dramatically for a period of about two days by the strong winds of typhoon during her passage. The result of observation showed that category 5 typhoon can affect the surface current in the radius of 860 km. Category 2 typhoon can affect in the radius of 680 km. The maximum observed current speed in the TS is 1.7 m/s southward corresponding to a category 2 typhoon, comparing with the normal northeastward flow pattern during summer monsoon season. On the other hand, surface velocity changed from the slow, northward current during pre-typhoon stage to the strong eastward current of 2 m/s under category 4 typhoon in the shelf-break of ECS (Chang et al, submitted to JO)

Observations of large amplitude non linear internal waves in the South China Sea

- A novel methodology and technology to observe large amplitude internal waves in the upper ocean from an array of drifting instruments was introduced. A detailed description of the methodology was discussed together with the characteristics of the instruments used, the ADOS-A (Figure 4), a drifting buoy that carries a 200 m long thermisthor chain, several profiling acoustic current meters and a GPS. Three packets of large amplitude, non-linear internal waves were observed in the South China Sea in 2007 (Figures 5 and 6). The velocity and direction of propagation of the waves within each group are accurately determined (Table 1 to 3) and their evolution over space and time scales comparable with those of the waves, as they propagate through the array, was studied. (Centurioni et al., submitted)

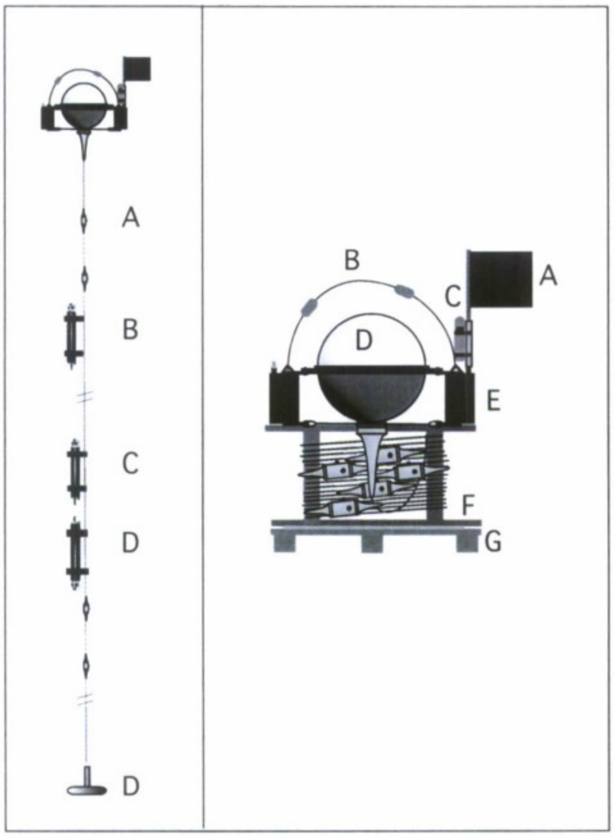

Figure 4. ADOS-A schematic. Left: the surface element is connected to a tether on which the temperature and pressure sensors (A), one 1MHz Aquadopp at 25 m depth (B), two 400 KHz Aquadopps (C and D) at 110 m depth and a 20 Kg weight (D) are attached. The spacing between the temperature and pressure sensors is approximately 10 m. Right: the ADOS-A tether is wrapped around a wooden reel (F) which is mounted on a pallet through a spinning wheel. The spherical buoy (D) is mounted on a rectangular cross-section toroidal anodized aluminum buoy (E). A flag (a) and a strobe light (C) are attached to the aluminum buoy together with a bridle used for recovering the ADOS-V.

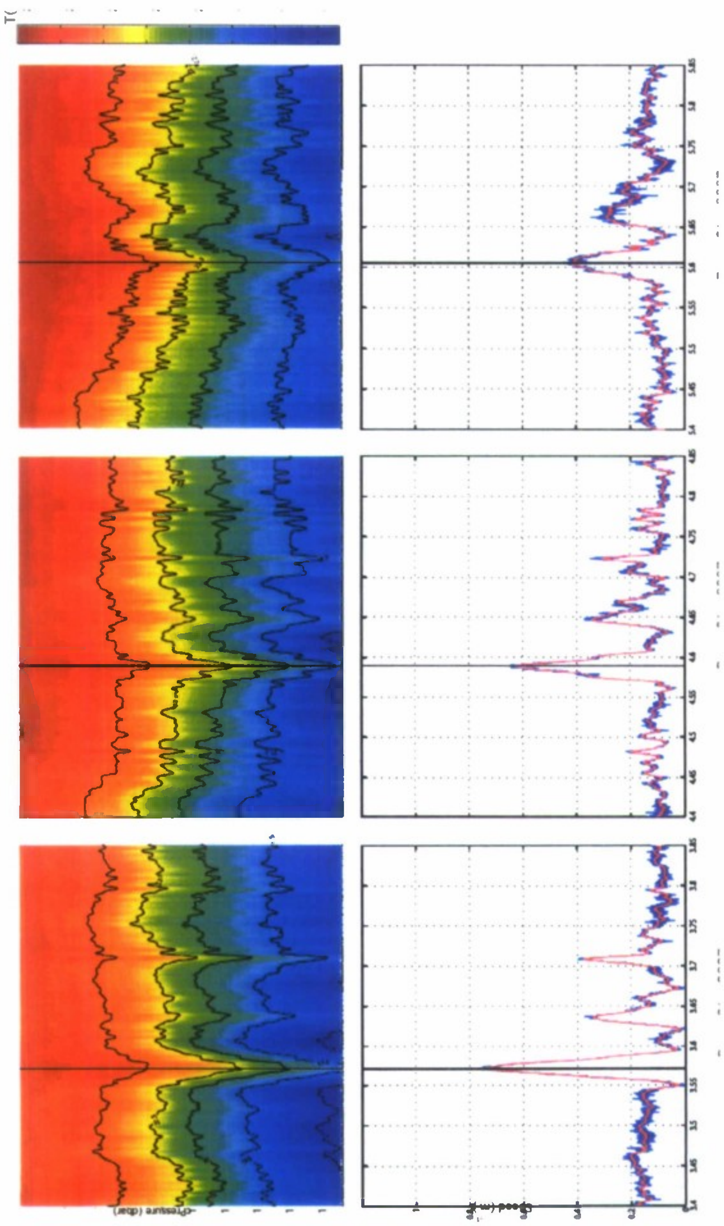

Figure 5: Observations of three wave groups from node 6. Top: isotherms displacement. Bottom: speed of the ADOS-A from GPS (blue are the 1 s data, red are the 30 s running averaged data). Data are plotted as time-series relative to the drifting instrument.

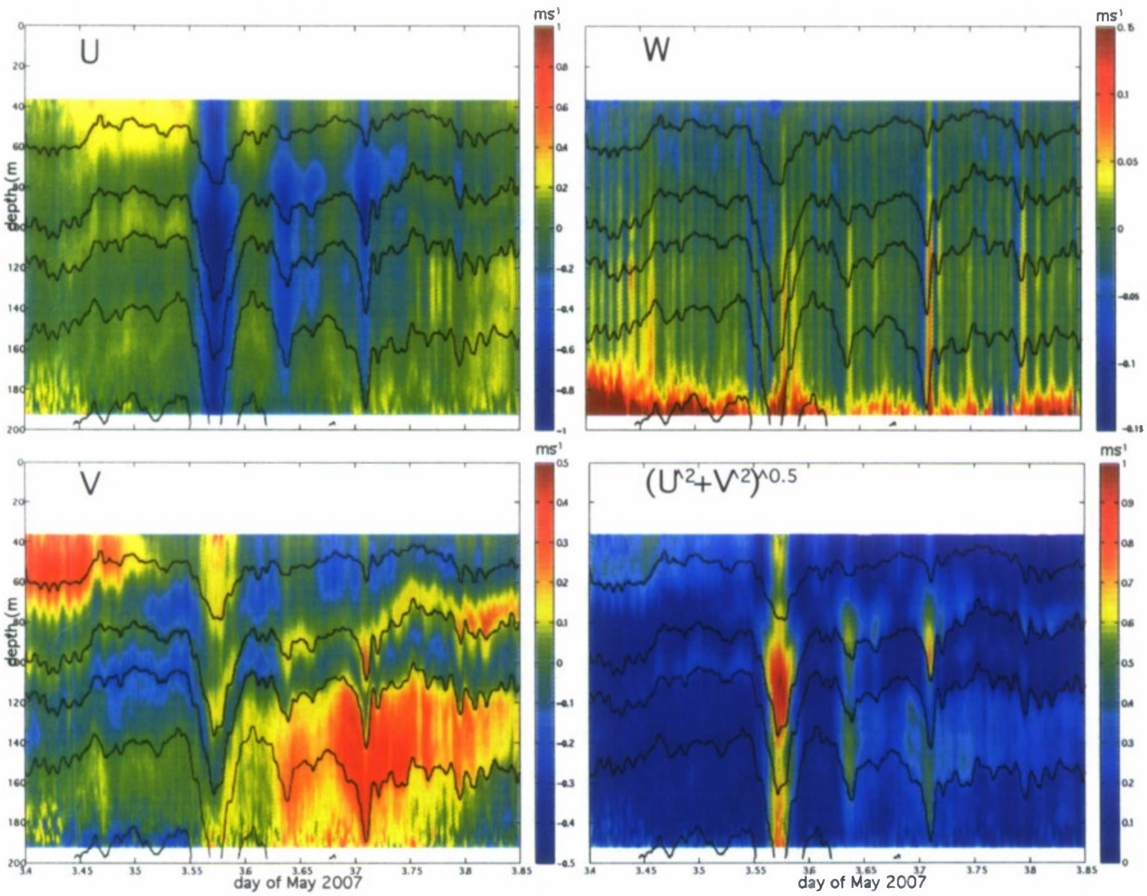

Figure 6. Three-dimensional absolute velocity profiles and horizontal flow speed measured from node 6. The following isotherms are also shown: 25°C, 22.5° C, 20° C, 17.5° C and 15° C. U, V and W are the eastward, northward and vertical upward velocity respectively

Table 1. *Speed and direction of propagation for the two main waves of group 1*

LIW group 1	Speed (m s^{-1})	Direction (°N)
Wave 1	2.80 +- 0.02	279.8 +- 0.5
Wave 2	2.60 +- 0.03	287.1 +- 0.7

Table 2. *Same as table 1 but for wave group 2*

LIW group 2	Speed (m s^{-1})	Direction (°N)
Wave 1	2.84 +- 0.03	282.6 +- 0.6
Wave 2	2.47 +- 0.05	285 +- 1

Table 3. Same as table 1 but for wave group 3

LIW group 3	Speed (m s^{-1})	Direction (°N)
Wave 1	2.79 +- 0.09	275 +- 3
Wave 2	2.57 +- 0.03	281 +- 1

STUDY OF KUROSHIO - EAST CHINA SEA INTERACTION USING ROMS

The model reveals that the alternating convergence-divergence zones are formed along the western boundary of Kuroshio (Fig. 7) and thus intrusion of Kuroshio water does not extend far into the shelf north of Taiwan. Northward along the ECS margin, where Kuroshio turns eastward direction following the topography, bottom water intrusions occur. During this deep-water intrusion process the surface layers form a convergent zone after the Kuroshio turn and all drifters that crossed the 200m isobath further south now rejoin the Kuroshio there (Fig. 8). Since the circulation in the ECS is mostly wind-driven, we are developing new mixing scheme for wind-driven current in the model of shallow water depth.

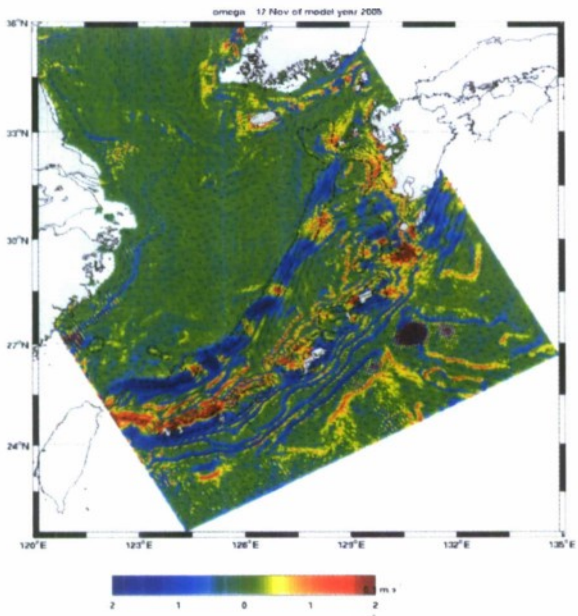

Fig. 7. Vertical velocity at 15 m depth from ROMS. Strong convergence zones appear along the western boundary of the Kuroshio.

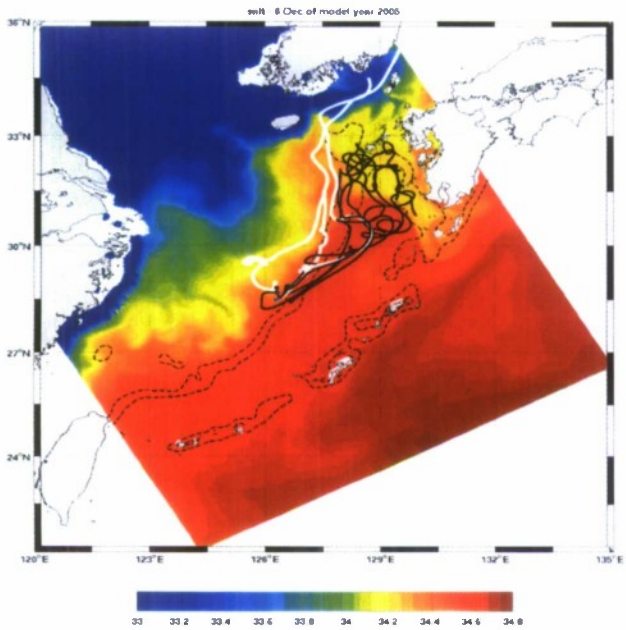

Fig. 8. Drifter tracks deployed on Oct-Dec. of 2007 and salinity distribution calculated from ROMS. The East China Sea fresh water joins the Kuroshio in the area west of Kyusyu.

OTHER RESULTS OBTAINED WITH PARTIAL SUPPORT FROM THIS GRANT

SVP drifter data from 1987 through 2005, AVISO sea level anomalies and NCEP reanalysis winds are used to assemble a time averaged map of the 15 m depth geostrophic velocity field in the California Current System seaward of about 50 km from the coast. The wind data are used to compute the Ekman currents which are then subtracted from the drifter velocity measurements. The resulting proxy for geostrophic velocity anomalies computed from drifters and from satellite sea level measurements are combined to form an unbiased mean geostrophic circulation map. The result shows a California Current System that flows southward with four permanent meanders that can extend seaward for more than 800 km. Bands of alternating eastward and westward zonal currents are connected to the meanders and extend several thousand of km into the Pacific Ocean. This observed time mean circulation and its associated eddy energy are compared to those produced by various high resolutions OGCM solutions: ROMS (5 km), POP (1/10°), HYCOM (1/12°) and NLOM (1/32°). Simulations in closest agreement with observations come from ROMS, which also produces four meanders, geostrophic time mean currents and geostrophic eddy energy that are consistent with the observed values. The time mean ageostrophic velocity in ROMS is strongest within the cyclonic part of the meanders and is similar to the ageostrophic velocity produced by non-linear interaction of Ekman currents with the near surface vorticity field (Centurioni et al. 2008).

IMPACT/APPLICATIONS

The drifter data were placed on the GTS for use by global scientific community.

TRANSITIONS

None

RELATED PROJECTS

The Global Drifter Program

PUBLICATIONS FROM THIS GRANT

Centurioni, L. R., Observations of large amplitude internal waves from a drifting array: instruments and methods, *submitted to J. Atmos. Ocean. Tech.*,under revision since 1/7/09

Centurioni, L. R., P. P. Niiler, and D. K. Lee, 2004: Observations of inflow of Philippine Sea surface water into the South China Sea through the Luzon Strait. *J Phys Oceanogr*, **34,** 113-121.

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Yu-Chia Chang[1], Ruo-Shan Tseng[1*], Luca R. Centurioni[2] and Dong-Shan Ko[3] , Typhoon-induced strong surface flows in the Taiwan Strait and the shelf-break sea, submitted to Journal of Oceanography, Jan. 2009

Chow, C. H., J. H. Hu, L. R. Centurioni, and P. P. Niiler, 2008: Mesoscale Dongsha Cyclonic Eddy in the northern Asouth China Sea by drifter and satellite observations. *J Geophys Res-Oceans*, **113,** -.

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